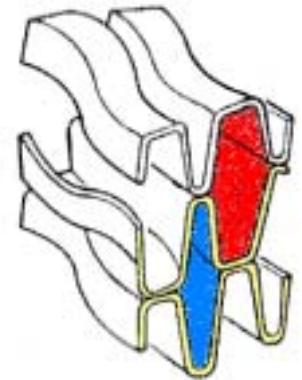


Cooperative Research and Development of Primary Surface Recuperator for Advanced Microturbine Systems

George Escola
Solar Turbines Incorporated
San Diego, California



2nd Distributed Energy Peer Review
December 2-4, 2003
Washington D.C.

Microturbine Recuperators Program Outline

- **Project Description and Goals / Objectives**
 - **Project Team / Partnerships**
 - **Task Definition and Activities Planned**
 - **Milestones Completed and Planned**
 - **Key Technical Barriers and Strategies to Overcome**
 - **Project Risks**
 - **Impact of Project on Goals of the Distributed Energy Program**
 - **Summary**
-

Project Description & Goals / Objectives



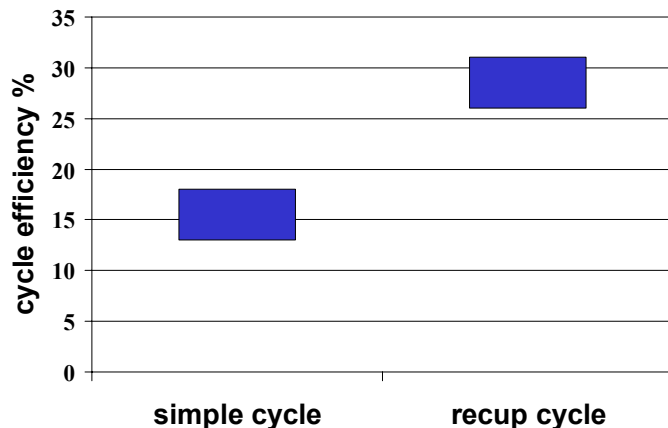
Improve the Durability and Cost Performance of Primary Surface Recuperators (PSR's) for Microturbine and Turbine Application:

- **Increase turbine exhaust temperature capability from 649°C (1200°F) to 732°C (1350°F)**
- **Contribute to microturbine goals of 40% efficiency, <7 ppmv NO_x, 11,000 hour minimum TBO life and 45,000 hour or better overall system life**
- **Assist microturbine manufacturers to offer more durable turbine systems that produce power at a competitive rate and allow greater market penetration**

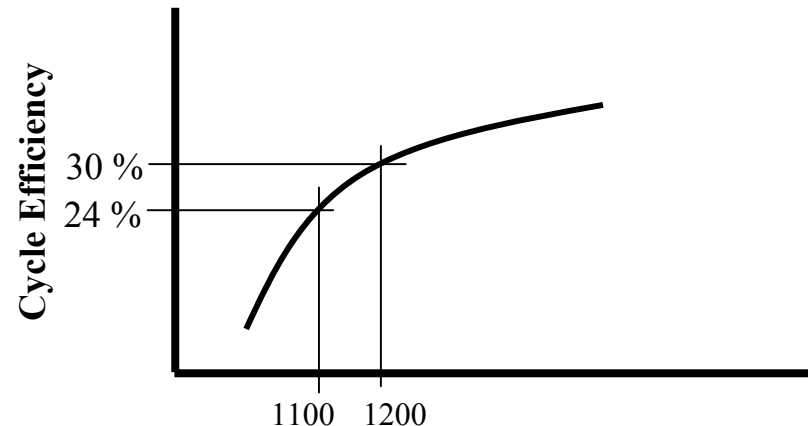
Project Description & Goals / Objectives

Recuperated Microturbine cycle efficiency increases with firing temperature.

However, selection of affordable materials often restricts recuperator exhaust-side inlet temperature thereby restricting turbine-firing temperatures.



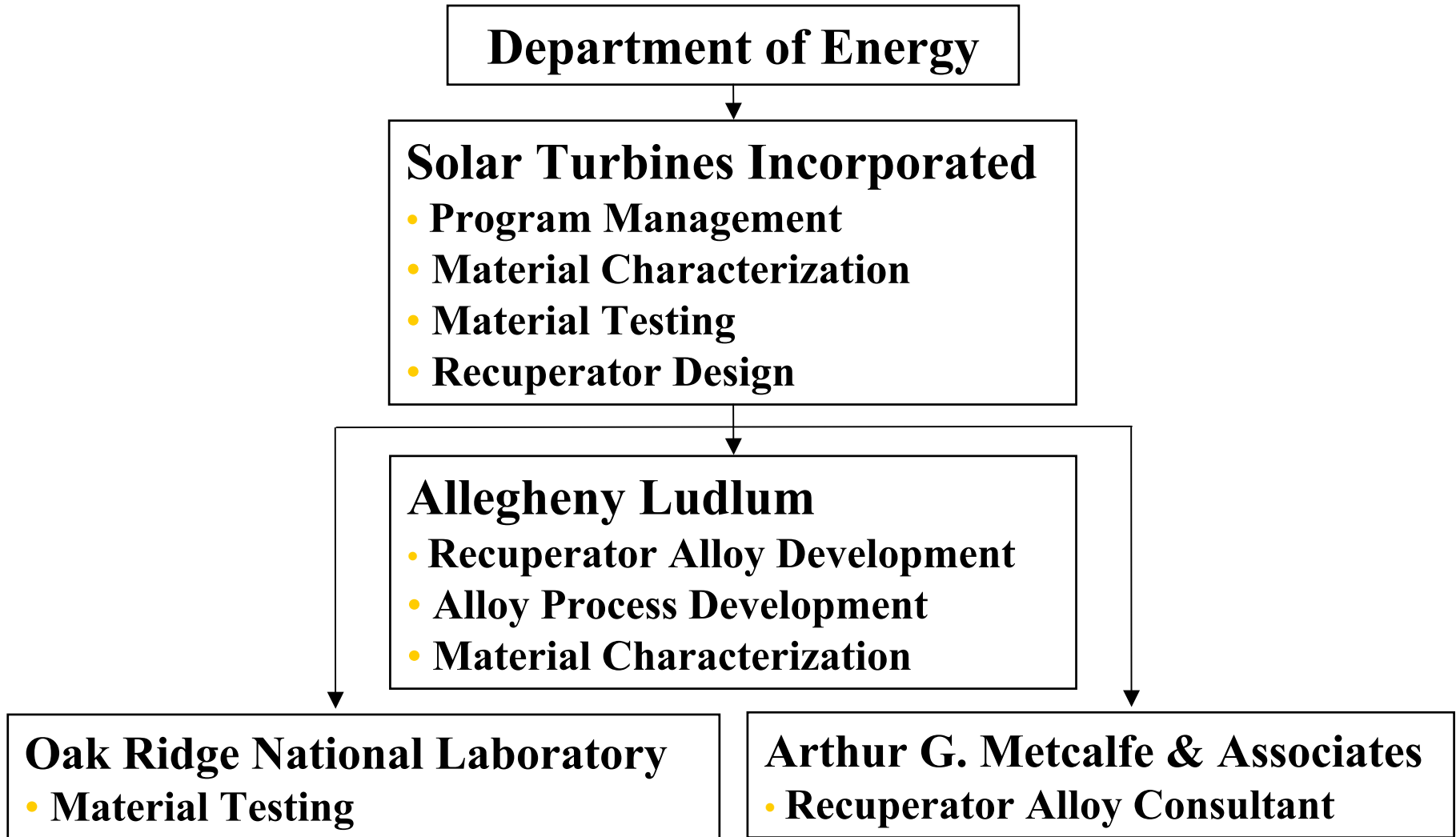
**Simple Cycle vs.
Recuperated Microturbine**



**Microturbine Exhaust Temperature
into Recuperator, °F**

Project Team / Partnerships

The Development Team



- **Program Sponsor**
 - **U.S. Department of Energy (DOE)
Office of Distributed Energy, Washington, DC**
 - **Debbie Haught, Merrill Smith**

- **DOE Project Management**
 - **DOE Chicago Operations Office, Argonne, IL**
 - **Dale Dietzel, Steve Waslo**
 - **DOE Golden Field Office, Golden, CO**
 - **Paul Bakke**

Task Definition & Activities Planned



- **Material Development**
 - **Creep-Resistant Type 347 SS Foil**
 - **Coated Type 347 SS Foil**
 - **Advanced Austenitic Foil**
 - **Coated Advanced Austenitic Foil**
 - **Dual Alloy Foil**
 - **Nickel-Based Alloy Foil**
- **Full-scale Recuperator Testing & Material Evaluation**

- **Material Development**
 - **Creep-Resistant Type 347 SS Foil**
 - **Coated Type 347 SS Foil**
 - **Advanced Austenitic Foil**
 - **Coated Advanced Austenitic Foil**
 - **Dual Alloy Foil**
 - **Nickel-Based Alloy Foil**
- **Full-scale Recuperator Testing & Material Evaluation**

Creep Resistant 347 SS Foil

Objective:

- Increase creep resistance through changes in manufacturing processes

Result:

- Lab heat material had 2X increase in creep resistance
- Oxidation properties limit life
- Down Selected

Coated Type 347 SS / Advanced Austenitic Foil

Objective:

- Coat material after recuperator manufacturing to increase oxidation capability

Result:

- Three coatings Studied
- All coatings failed due to spalling

Advanced Austenitic Foil

Objective:

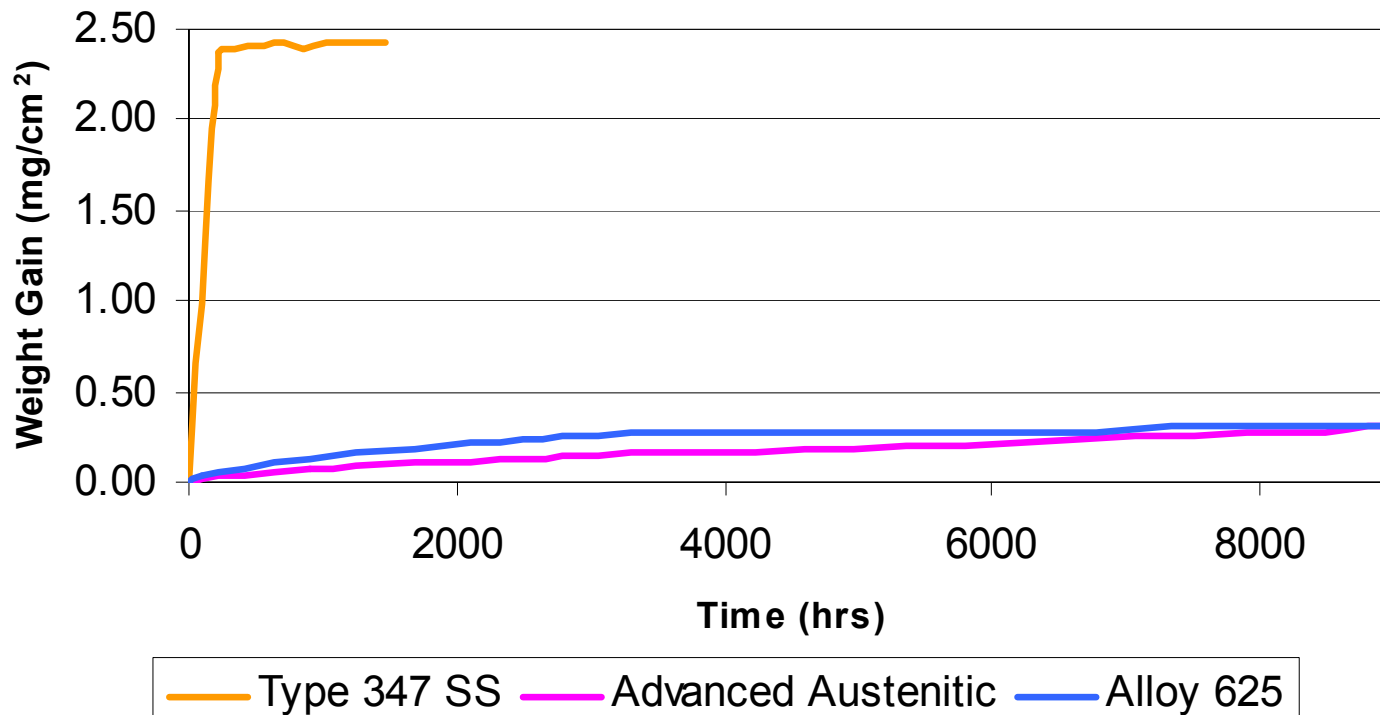
- **Develop a higher temperature advanced austenitic foil**
 - with less than 1.4 - 1.6X cost of 347 SS
 - and a 1250 °F or greater capability

Result:

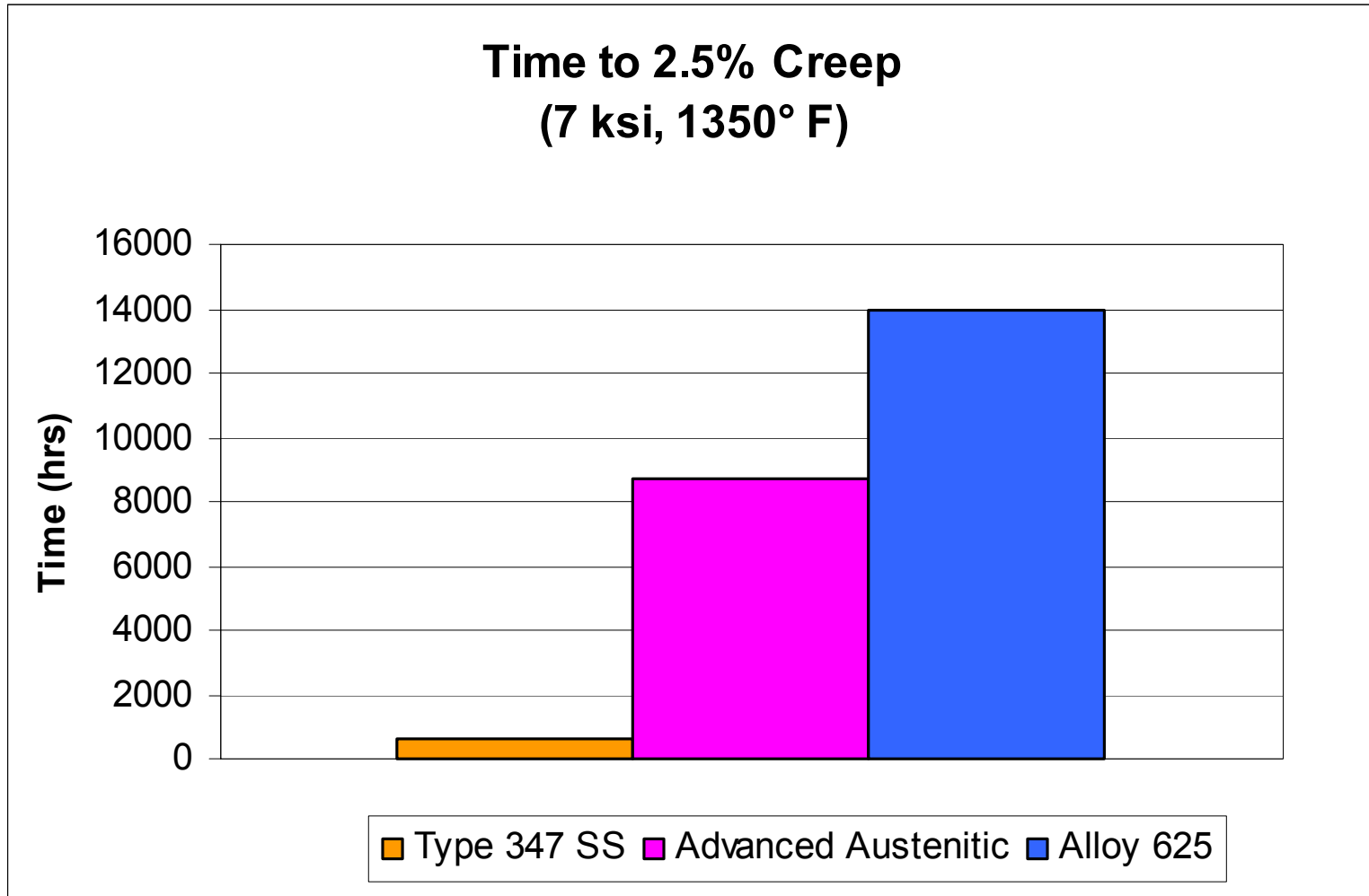
- **Lab heat material has 8X increase in creep resistance over Type 347 SS**
- **Oxidation resistance superior to alloy 625 in water vapor**
- **Mill run has similar properties to Lab Melt**
- **Mill run Processed into Plate, Sheet and Foil**
- **Cost Under Target in Production Quantities**

Materials Development - Advanced Austenitic

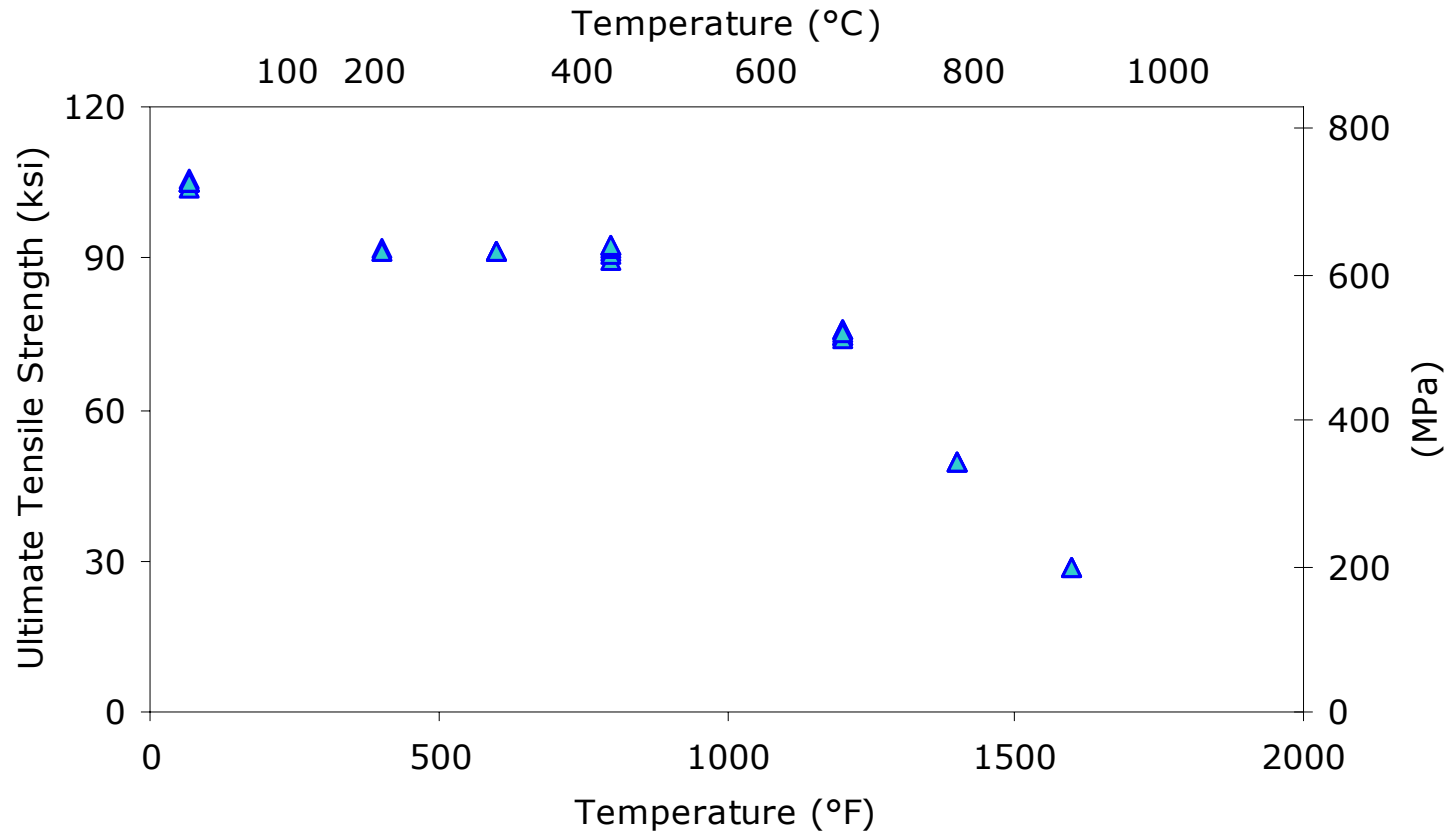
Oxidation Test Results (7% Moisture, 1300°F)



Materials Development - Advanced Austenitic

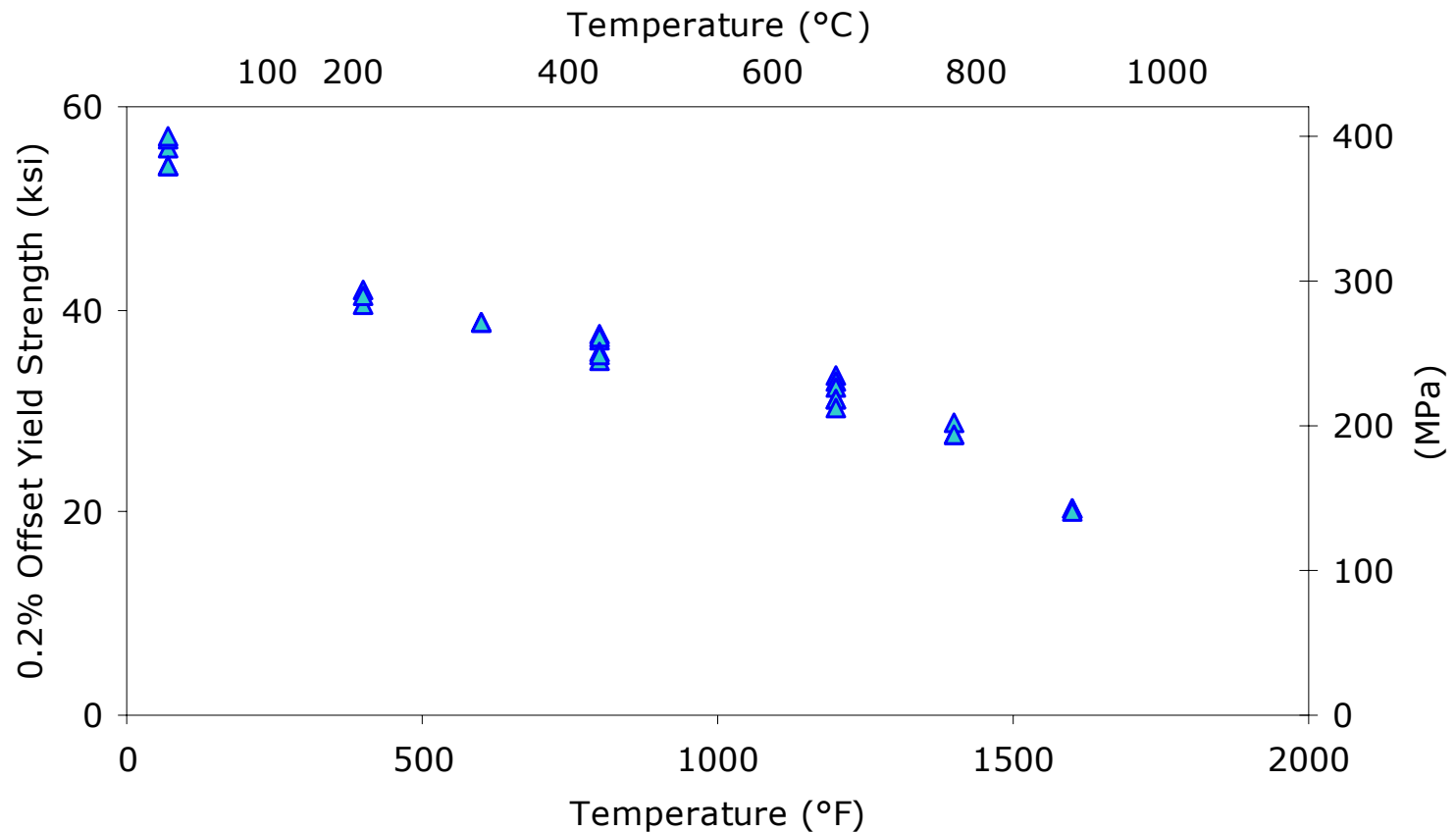


Materials Development - Advanced Austenitic



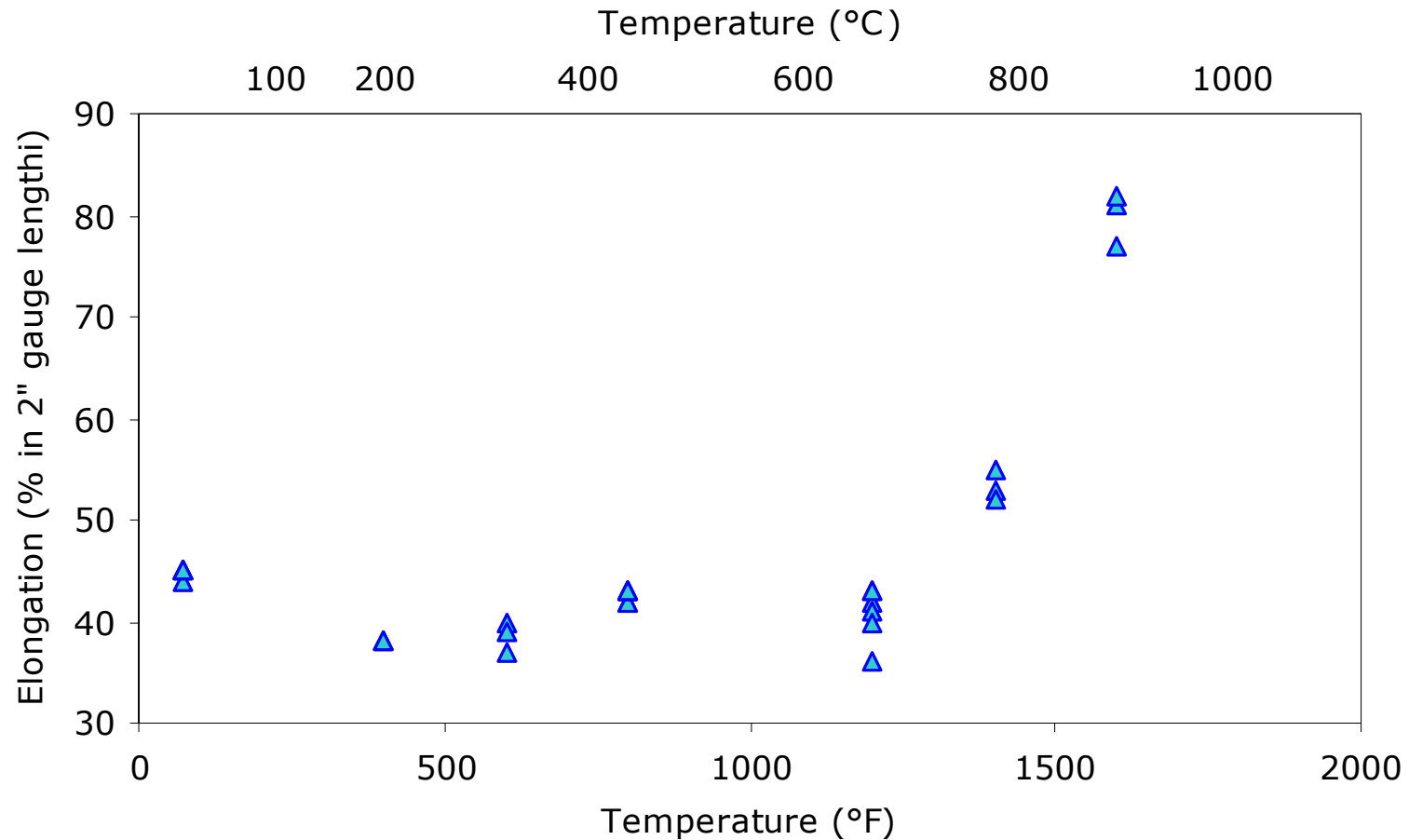
Ultimate Tensile Strength

Materials Development - Advanced Austenitic



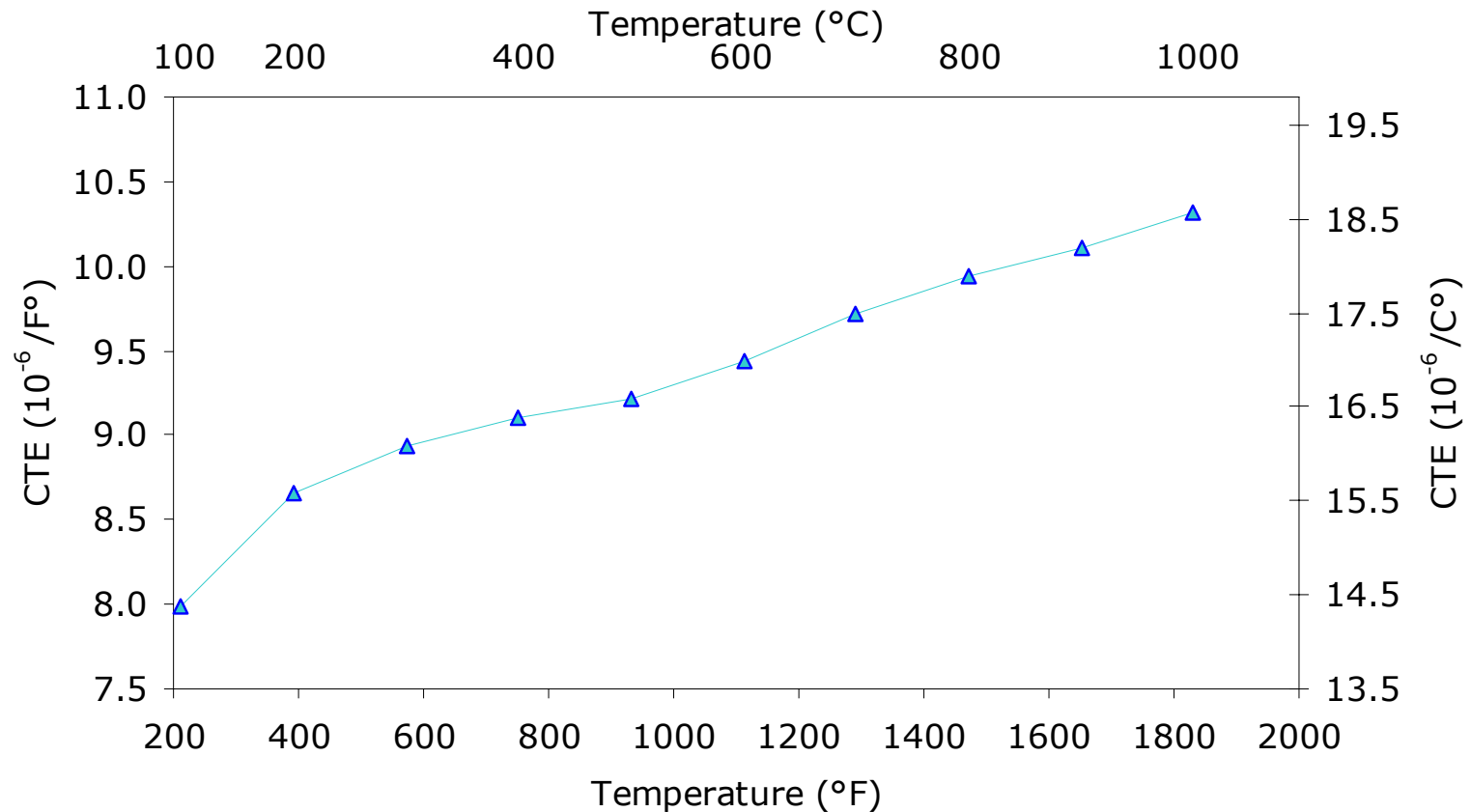
0.2% Offset Yield Strength

Materials Development - Advanced Austenitic



Elongation

Materials Development - Advanced Austenitic



Coefficient of Thermal Expansion

Dual Alloy Foil

Objective:

- **Develop a dual alloy system for higher oxidation resistance and creep strength**

Result:

- **Seam welding process requires accurate fixturing**
- **High cost of materials and processing**
- **Down Selected**

Nickel-Based Foil

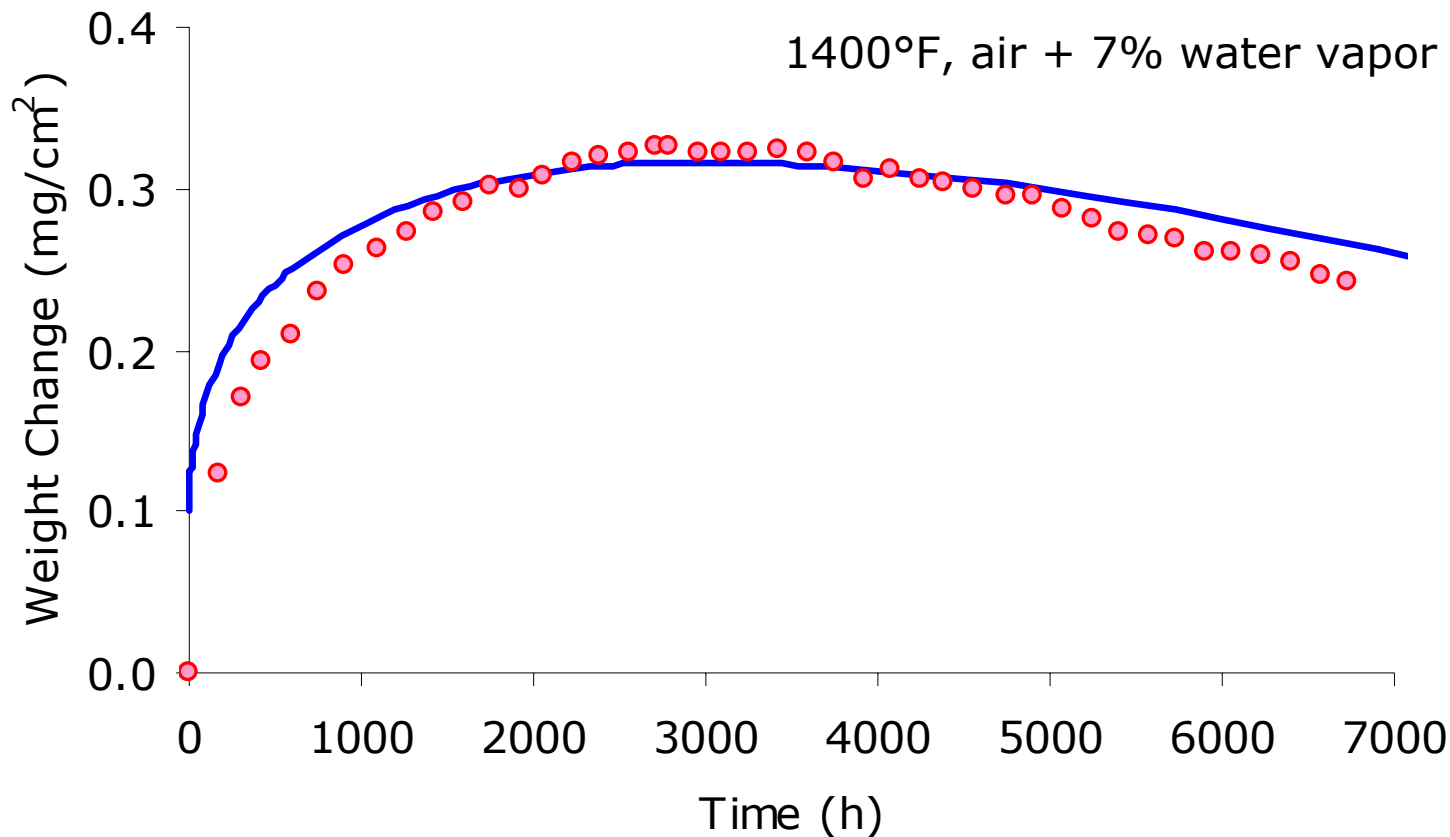
Objective:

- Evaluate Alloy 625 and Haynes 230 for
 - Oxidation Resistance
 - Creep and
 - Manufacturability

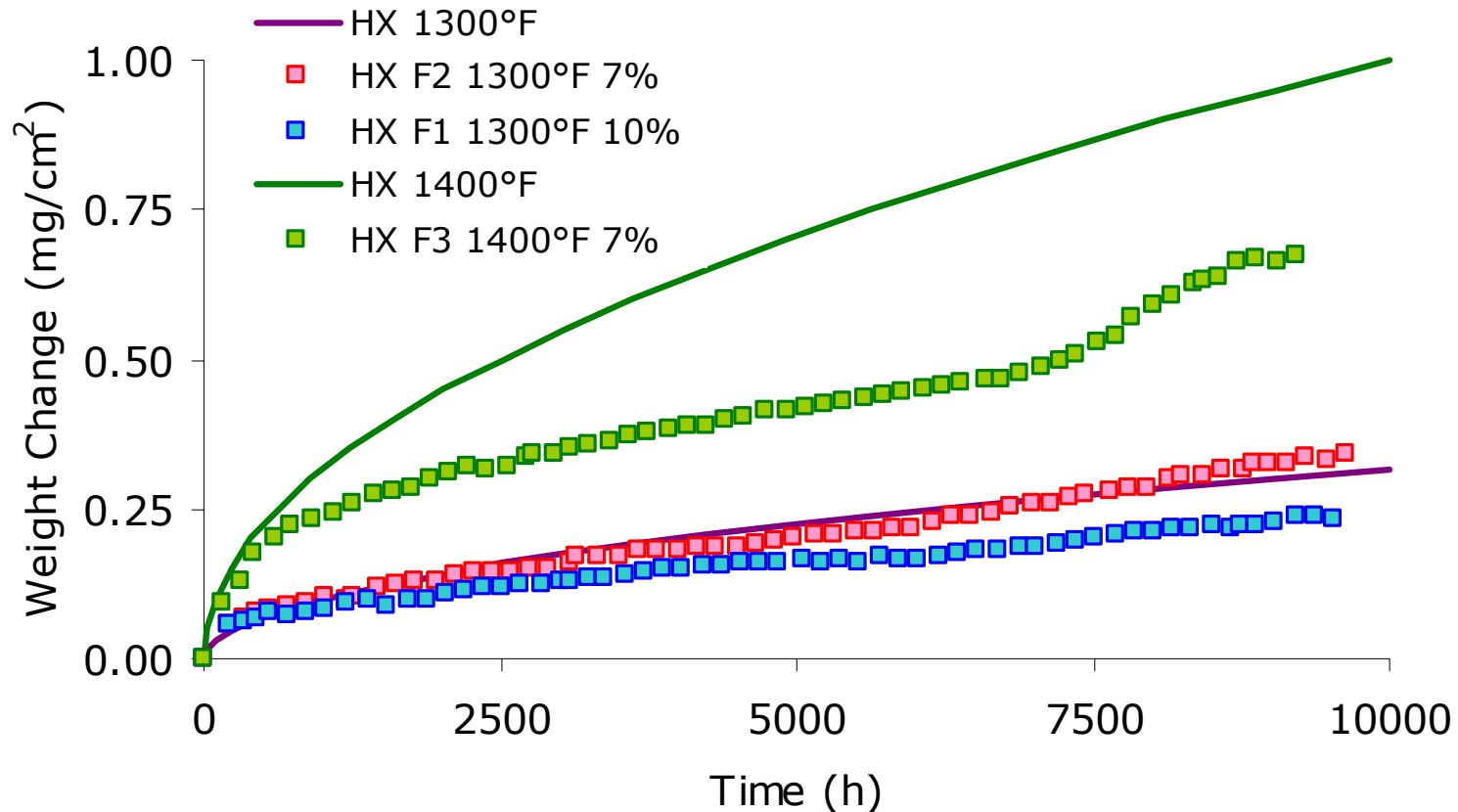
Result:

- Alloy 625 Selected for Full-scale Recuperator Testing
- Oxidation and Creep Testing Complete
- Folding and Welding Tests Complete
- Recuperator Built and Testing is Underway

625 Alloy—Oxidation Testing



HX Alloy—Oxidation Testing



- **Water vapor promotes oxide scale evaporation for 625 alloy**
- **HX alloy does not tend to exhibit excessive scale evaporation**
- **Accelerated oxidation not observed after 10,000 hours of testing**
- **Ultimate failure mode for Ni–base alloys not yet documented**

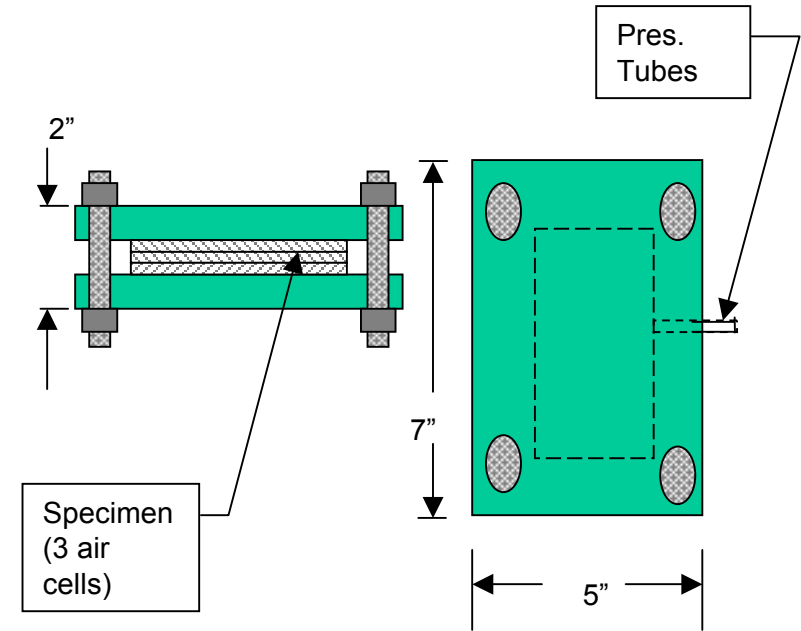
Microturbine Recuperator Alloy Selection Process

Approach	Optimize Type 347 SS		Use a Nickel Base Alloy	Develop an Iron Base Alloy	
	Coated	Clad	Alloy 625	AA	Coated AA
Oxidation	Fail	Marginal	Pass	Pass	Fail
Creep	Marginal	Marginal	Pass	Pass	Pass
Formable/Weldable	Marginal	Marginal	Pass	Pass	Marginal
Cost	Marginal	Fail	Marginal	Pass	Marginal
Overall	Fail	Fail	Pass - Marginal	Pass	Fail

**Alloy 625 and Advanced Austenitic (AA) Foil
were Selected for Full-scale Recuperator Testing**

Creep Core Testing

- **Testing By ORNL**
- **Specimen Materials**
 - 347 SS
 - Advanced Austenitic
 - Alloy 625
- **Eight Test Specimen**
 - 3,000 Hour Tests to Match Current Experience
 - 7,500 Hour Tests to Simulate Desired Life of 30,000 & 60,000 Hours
- **500-Hour Test System Checkout Underway**



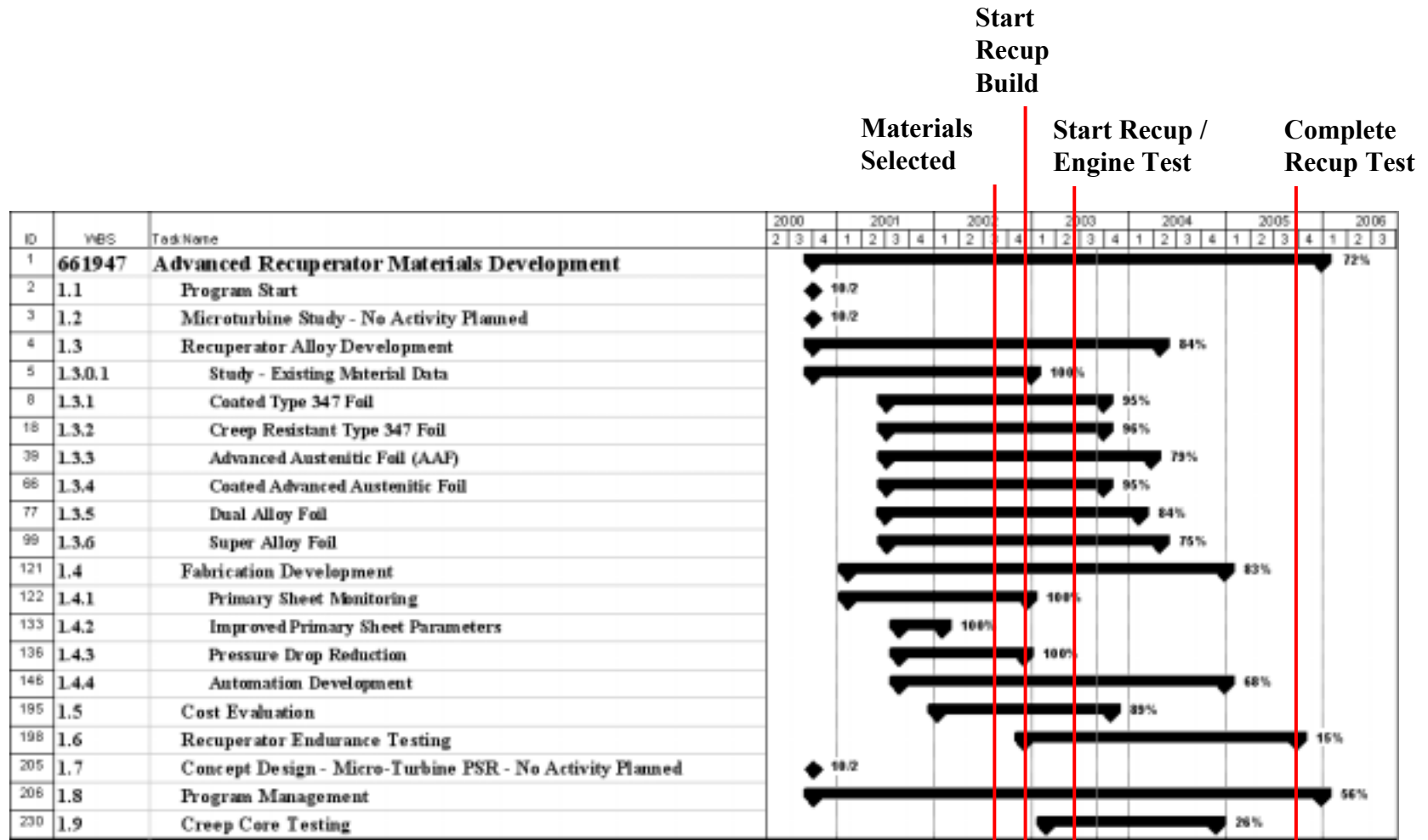
- **Material Development**
 - Creep-Resistant Type 347 SS Foil
 - Coated Type 347 SS Foil
 - Advanced Austenitic Foil
 - Coated Advanced Austenitic Foil
 - Dual Alloy Foil
 - Nickel-Based Alloy Foil
- **Full-scale Recuperator Testing & Material Evaluation**

Full-scale Recuperator Testing & Material Evaluation

- **Full-scale Alloy 625 Recuperator Started Test in August 2003**
- **Coupons for Oxidation & Creep Testing to be Pulled Every 1,000 Hours**
- **Full-scale Advanced Austenitic Recuperator to Build for Testing in 2004**

Milestones Accomplished & Planned

Program Schedule



Milestones Accomplished & Planned

Recuperator Build (Alloy 625)	Dec. 2002	Complete
Start Recuperator Testing (Alloy 625)	Jun. 2003	Complete
Deliver Adv. Austenitic Material	Jun. 2003	Complete
Start Creep Core Testing	Sep. 2003	Complete
Start Fin Folding Design of Experiment	Oct. 2003	Complete
Start Recuperator Build (Adv. Austenitic)	Jan. 2003	
Start Recuperator Endurance Test (Adv. Austenitic)	Jun. 2004	
Materials Evaluation Report / Project complete	Sep. 2005	
Final Report	Dec. 2005	

In Progress / Future Work

- **Alloy 625**
 - **Continue to characterize oxidation and creep properties**
 - **Evaluate recuperator core/specimens after engine test**
- **Advanced Austenitic**
 - **Build Recuperator**
 - **Evaluate recuperator core & coupons after engine test**

Key Technical Barriers & Strategies to Overcome

Key Technical Barriers & Strategies to Overcome

- **Lab to Mil Scale-up**
 - **Physical properties are consistent**
 - **Prove consistency of long-term properties**
- **Capability to Fabricate Recuperator Components**
 - **Formability**
 - **Weldability**

Project Risks

- **Lab to Mill Scale-up**
 - **Inconsistent properties**
 - **Schedule and Budget constraints may impede further development work**
- **Mill Materials to Recuperator Cores**
 - **Properties from lab tests don't replicate**
 - **Formability and/or weldability don't meet requirements**
- **Recuperator Testing**
 - **Durability doesn't meet requirements**

Impact of Project on Distributed Energy Program

Impact of Project on Distributed Energy Program

**The Microturbine Recuperator Program is
designed to Promote Distributed Energy By:**

- **Contributing to Microturbine goals of 40% efficiency, <7 ppmv NOx, 11,000 hour minimum TBO life and 45,000 hour or better overall system life.**
- **Assisting Microturbine manufacturers to offer more durable, cost effective systems that produce power at a competitive rate and allow greater market penetration.**

Summary

- Alloy 625 offers excellent high-temperature properties, but at high cost
- Advanced Austenitic offers higher exhaust temperature capability than 347 SS with superior oxidation and creep strength at reasonable cost
- Solar Turbines and Allegheny Ludlum continue to characterize Alloy 625 and Advanced Austenitic materials for Microturbine Recuperator applications
- Inquiries about Advanced Austenitic can be directed to Allegheny Ludlum

Cooperative Research and Development of Primary Surface Recuperator for Advanced Microturbine Systems

Questions

